

27th CIRP Design 2017

Axiomatic Design of equipment for analysis of SMA Spring degradation during electronic actuation

Einar Pétursson^a, Ingi Níels Karlsson^a, Olaf Garðar Garðarsson^a, Páll Pálsson^a, Saulius Genutis^a, Vladimir Omelianov^a, Joseph Timothy Foley^{a,*}

^aReykjavík University, Menntavegur 1, Reykjavík 101, Iceland

^{*} Corresponding author. Tel.: +354-599-6569; fax: +354-599-6201 E-mail address: foley@ru.is.

Abstract

The Shape Memory Alloy, Nickel-Titanium i.e. Nitinol is greatly lacking in published research about its properties. Both degradation through electronic actuation and degradation through heat actuation are lacking, as well comparison of them. This means that both inventors and manufacturers are missing important information, limiting their ability to reliably apply the material in the soft robotic field, automotive design, consumer electronics, or aerospace. Accurate and reliable testing equipment is essential to gather needed data about the material for further development. This paper presents a static test bench for SMA springs that is designed according to Axiomatic Design Theory. The tester is designed to actuate and measure six springs at a time to increase the rate at which testing data is gathered. The measurements collected are the force, current, and temperature of each spring along with the ambient temperature. The test bench was successfully designed and built. An initial test run lasted for two days for approximately 6700 cycles; no springs experienced a complete failure.

© 2017 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference

Keywords: Axiomatic Design, Shape-Memory Alloy, Nitinol, Springs, SMA life-cycle

1. Introduction

Shape Memory Alloy (SMA) are alloys that can “remember” their shape: if the material is deformed it can reach its original shape by being heated to a certain temperature.

Springs made from Nickel-Titanium Alloy (NiTi i.e. trade name Nitinol) are rarely investigated so information about their abilities under different conditions is minimal. Because of little available performance they are not often used in an actuation capacity, only in a super-elastic mode. Consequently, SMA-specific testing equipment is not commercially available. Actuator performance over its lifetime, especially degradation, is essential for designers and manufacturers to use NiTi as a material of choice. Manufacturers can not produce actuators without known specifications and expect customers to buy them.

SMA's actuation mechanism in its raw state is that of small angular bending or very small strains, 3% or less. One way to increase the strain at a significant drop in generated force is to wind the SMA into a spring shape [1,2]. The objective of this project was to use Axiomatic Design Theory [3] to design a test bench that can quantify the performance of springs made of NiTi focusing on degradation. Electronic heating actuation was explored due to its convenience in engineering ap-

plications. A test bench capable of recording force generated to correlate with current and temperature will be valuable for designers of actuators or manufacturers desiring to use Nitinol.

Nomenclature

AD	Axiomatic Design
SMA	Shape Memory Alloy
NiTi	Nickel Titanium alloy or Nitinol
C_n	Constrain n
FR_n	Functional Requirement n
DP_n	Design Parameter n

2. Background

In late 1950's, William Buehler discovered abilities of NiTi, or as often commercially called “Nitinol”. This was at the Naval Ordnance Laboratory (NOL) while researching heat resistant alloys for weapon development [4]. SMA has a “one-way” and “two-way” memory effect of its solid-solid transformation from low-temperature martensite to the high-temperature austenite

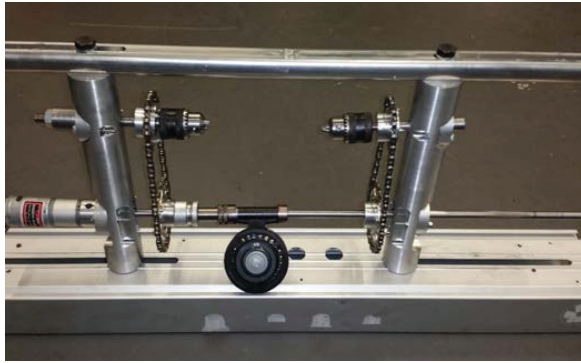


Fig. 1: Spring winder used in project

phase. In this research, we used one-way memory effect Nitinol where an external force is needed to return it to the martensite state. Two-way memory effect is when the alloy changes its phase between austenite and martensite phase without any externally mechanically applied forces, though it can not provide any force to external components in the phase changing [2].

2.1. Existing equipment

When the authors started working on the design, some existing equipment for conducting research on SMA springs was available from the previous work by Einarsson [5]: a single-spring spring tester, a spring winder, and a prototype spring winder frame which was much lighter (Fig. 1). The spring winder was assembled on the new frame for convenience and used to produce springs for use in testing.

The spring-winder consists of a DC brushed motor, fishing reel, axle, and chains for rotating the core. On the lower axle is the motor and fishing reel filled with NiTi wire; the reel provides adjustable tension for consistent winding. A core wire that defines the inner diameter of the spring is attached to the two drill chucks on the upper axle and pulled under tension. The SMA wire is attached to the core and motor engaged for winding the wire on the core. This procedure produces we get one long spring (approximately 10 cm) that is then cut down to appropriate test sizes. By winding one long spring, we can ensure a consistent winding angle for a single set of test samples.

Einarsson's spring tester [5] was made to test one spring at the time using a lever to scale the force on the load cell to be able to test a wider range of springs with a single load cell. The instrument measured tension force from the spring while heated at a fixed current of 5.3 A on a National Instruments (NI) USB-6008 12-Bit, 10kS/s Low-Cost Multifunction DAQ. The graphical user interface and data processing were developed on NI Lab View. The main complaint about this tester was that it took too long to get sufficient data for analysis.

2.2. Considerations for new design

The new test bench that was made in this project (Fig. 2) was designed to test six springs simultaneously to reduce testing time and to get acceptable sample size of data. Choosing the number of simultaneous tests originates from the basics of small sample statistics: Student's t distribution. Normally, it is

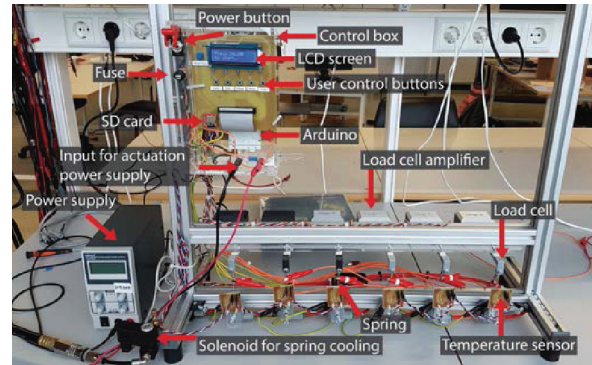


Fig. 2: Completed SMA spring test bench

assumed that small samples $n \leq 30$ adhere to a normal distribution when taken from known normally distributed populations. The Student's t distribution allows us to calculate the required sample size to ensure that the mean of the samples matches the population mean within a certain error limit [6]

$$\delta > t_{\text{crit}} \sqrt{\frac{2\sigma^2}{n}} \quad (1)$$

where

n is the number of samples

σ^2 is the estimated population variance

t_{crit} is the critical value of Student's t read at degrees of freedom $n - 1$ and $P = 0.05$

At sample size $n \geq 6$ the determination of significance drops to below half of the estimated population standard deviation. We consider this good enough estimator to provide information on the population of SMA springs created in the same manner to allow aggregate data analysis.

Each spring is directly connected to a load cell and measures tension force; this improves accuracy by removing sine error but means that the load cells must be matched to the expected spring actuation force. Spring temperature, ambient temperature and current through each spring is also measured. The bench also includes a dummy load cell as a base reference for possible environmental changes that might influence measurements.

There are many spring testers available on the market today. United Testing System from Canada offers for example ESM 303 [7]. However, these testers are focused on measuring the spring constant of a compression or extension spring, not on active actuation. It is possible that the tester could be adapted to measure SMA springs, but we could not find any existing systems suitable. An added complication is the large cost usually associated with such industrial instrumentation.

3. Design Attributes

To get the widest data and minimize the time it takes to obtain it we followed Axiomatic Design Theory (AD) [8]. AD

can be described as a design method that focuses on reducing design iterations through analysis of coupling factors and complexity. Complexity in this context is the information content: in short, how often does the design fail to meet its requirements [3]. The AD process begins with listing out the Customer needs (CN). The CNs are then translated into Functional Requirements (FR). For each FR a corresponding Design Parameter (DP) is defined. The DP is a definition on how the design will achieve the FR. The AD process then “zig-zags” between FR and DPs at each level so that constraints or attributes imposed by a previously chosen DP can be handled in lower layer FR and DPs. FRs should be collectively exhaustive and mutually exclusive (CEME) [9]

3.1. Constraints (C)

A set of constraints was generated from the project environment and scope:

C₁ Total cost must not exceed 100000 ISK.

C₂ The unit must be complete in 12 weeks.

3.2. Customer Needs (CN)

The team first investigated the customer Needs (CNs) by first asking, “What kind of customers should this project be aimed at?” It was clear that our prototypical customer would be a soft robotics company that would be using SMA springs in their design [1]. Based upon that industry’s needs, the correct SMA wire diameter coupled be chosen for the expected force range of up to 9.81 N

To implement customer needs using Axiomatic Design theory [10] we needed to define our top level CN₀.

CN₀ Provide detailed data on NiTi spring performance, regarding degradation and longevity.

CN₁ Be able to test NiTi springs with electrical actuation.

CN₂ Be able to test six springs at a time (See Section 2).

CN₃ Test springs with tensile force up to 9.8 N.

3.3. Functional Requirements (FR)

Customer needs were refined into demands by the customer for the specific functionality of the device. Best practices for FRs are that they must start with an action or transformative verb and able to be validated. [10,11]

FR₀ Test degradation and longevity of NiTi springs

FR₁ Fix 6 springs in testing bed simultaneously

FR₂ Actuate springs

FR₃ Measure force of each spring

FR₄ Measure temperature of each spring

FR₅ Cool the springs

FR₆ Record spring data

3.4. Design parameters

To be able to fulfill the FRs, the team generated a possible solution with Design Parameters (DPs) to meet each FR. Best practices indicate they must start with a noun and be something that can be compared or quantified [10,11].

DP₀ Spring tester

DP₁ Test bed with 6 locations to mount springs

DP₂ MOSFET connection to power supply controlled by micro-controller

DP₃ Load cell with range to match expected spring force

DP₄ IR thermometer

DP₅ Compressed air directed on springs

DP₆ Arduino Mega with SD card

4. Design

We can see the coupled design matrix in Eq 2.

$$\begin{pmatrix} \text{FR}_1 \\ \text{FR}_2 \\ \text{FR}_3 \\ \text{FR}_4 \\ \text{FR}_5 \\ \text{FR}_6 \end{pmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & X \\ X & X & X & 0 & 0 & 0 \\ X & X & 0 & X & 0 & 0 \\ X & X & 0 & 0 & X & 0 \\ X & X & X & X & X & X \end{bmatrix} \begin{pmatrix} \text{DP}_1 \\ \text{DP}_2 \\ \text{DP}_3 \\ \text{DP}_4 \\ \text{DP}_5 \\ \text{DP}_6 \end{pmatrix} \quad (2)$$

The matrix is almost decoupled i.e. path-dependent, but there are a few coupling elements outside of the triangle. Another heavily coupled item is DP₆ the Arduino Mega as it activates the springs, air cooling system, and collects data from all the sensors. This high-level of coupling indicates that larger resources should be spent making sure that it does not delay or complicate other elements of the implementation.

4.1. Hardware

The hardware design can be seen in Fig. 3. The control box is located on top of the bench for easy access and for easier wiring. The test bench is fully mobile but needs an external power source and compressed air supply. The test bench DP₁ and FR₁ require the test bench to be able to test 6 springs at a time and therefore six testing modules including load cells were mounted to the frame. Determine the effect room temperature has on the load cells for later normalization, a neutral load cell was added on the back of the bench. The results from the cell are used as a calibration reference for the other load cells.

The frame is made out of extruded aluminum profile for adjustability. It can be adapted for a wide range of spring lengths and diameters. The adjustable axis can be seen in Fig.4.

Complex Parts were printed in a Ultimaker 2 Extended+ out of PLA (polylactic acid) chosen for minimal shrinkage: upper spring holder, amplifier box, and the lower spring holder. Flat geometries such as mounts for the IR sensors were cut on an Eclipse Laser 30 W Fusion M40 laser cutter in 4 mm acrylic.

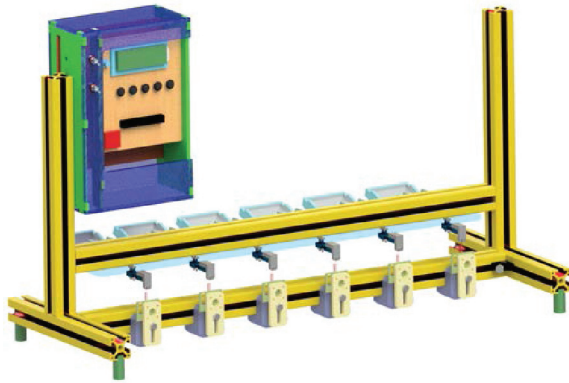


Fig. 3: CAD model of complete Test bench assembly.

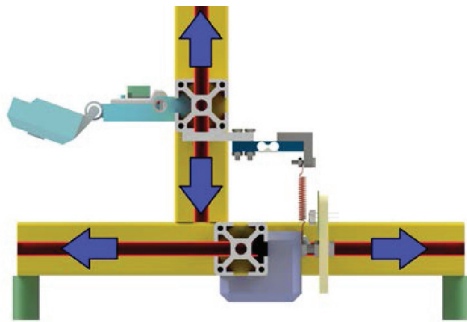


Fig. 4: Cross-section showing adjustable components of the test bench.

To make sure the SMA wire would not melt the plastic in the holder and increase the cyclic rate for testing, air cooling is routed through tunnels around the bolt hole that holds the lower part of the spring. By 3D printing those parts we were able to full fill our constraints C_0 and C_1 , which were keep the cost and manufacturing time down by using cheap PLA plastic while simultaneously working on other parts while printing. The air tunnel outlet is at an angle to blow air at the SMA wire. Since there is no way of changing the angle of the air that comes out of the lower spring holder the lower bar that holds it was made adjustable.

On Fig. 3 there can be seen the control box that was designed to hold the two circuit boards that were made. It is assembled out of 7 individual pieces of plastic that were designed to hold the boards in place and have enough space for all the wiring. On the front are two main switches to turn on and of the test bench. The box is open for access to the circuit board that in the front since it contains the controls the to the setup and SD card.

In front of each spring is an infra-red temperature sensor that is held with a plate that is made out of plastic cut out with a laser cutter. The bracket was made adjustable since the temperature sensor has to be able to point at the SMA wire which may vary a few mm in placement.

4.2. Electrical

The electrical design was guided by the independence axiom [3]. One power supply for actuation and a separate one

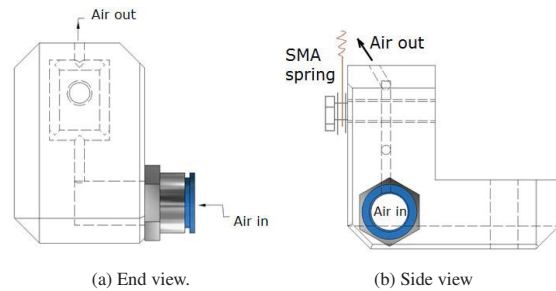


Fig. 5: Lower spring holder, fabricated with 3D printer. Note the embedded air cavities for directing the air flow from a pressurized source.

for control and sensors. This design setup ensures that voltage drop caused by actuation sudden switching does not affect the control system or sensors.

To keep the design within cost constraints, the price of electrical components highly influenced component selection. To interface with all of the sensors an Arduino Mega was chosen as a controller. Other electrical components are:

- Melexis MLX9061ESF-BAA IR Thermometers
- AliExpress 500g 1.1lb Aluminium Alloy Micro Load Cell Weighting Pressure Sensor
- Sparkfun HX711 Load Cell Amplifiers.
- Arduino Mega 2560 R3
- Adafruit INA219 High Side DC Current sensor breakout (26 V)
- 2×8 LCD screen to display status.
- Control buttons.
- Sparkfun microSD Transflash breakout
- IRF3205 MOSFET Transistors for SMA spring actuation.

Additionally, to keep costs to a minimum, all PCBs were a single layer and produced on site.

Because the load cell's Wheatstone bridge only have an output rating of 4 mV V^{-1} , the signal needs to be amplified. The HX711 amplifier converts the small analog signal from the load cell to a numeric value that is sent to the Arduino with a serial interface. To prevent interference from the surroundings the amplifier had to be placed as close as possible to the load-cells, making the length of wire carrying the analog signal from the load cells as short as possible.

4.3. Software

The program is written in C++ using Arduino IDE and Eclipse software packages. The following libraries were used in order to complete the design:

LiquidCrystal: LCD interface

SD: SD-card reading and writing

SPI: Dependency for the SD library

SparkFunMLX90614 interface for IR sensors

Adafruit_INA219: interface with the Adafruit current sensors

Wire: I2C API dependency for communications with IR and current sensors

HX711 interface for load-cell amplifiers

4.3.1. Operation

The structure of the device software is an FSM (Finite State Machine) with the following states:

1. On
 - Setup number of springs
 - Check the presence of SD card
 - Check if SD card is correctly setup
2. Calibration
 - Calibrate the load cells
3. Running
 - Create new file on SD card for data
 - Create a string with measurements:
 - Time since power on (ms)
 - Load cells load for each spring (N)
 - Springs temperatures (°C)
 - Ambient temperature (°C)
 - Current of each spring (mA)
 - Cycle count (once all working springs have reached the set threshold force, or 20 seconds pass cycle is finished — the current for springs cuts off and air pump turns on for 2 seconds in order to cool down the springs)
 - Count of broken springs (once current sensor detects current that is less than 10 mA, it counts a spring as a broken one)
 - Writes a data string to SD card
4. Pause (When paused, power to springs cuts off)
5. Done (All springs are broken, current on all springs is less than 10mA)
6. Error (If error occurs, current to springs will be cut off and user will be required to press “Enter” button to restart the cycle)

LCD shows the status of the test and provides necessary information for observations such as:

1. Time since test started
2. Number of broken springs
3. Number of cycles
4. Temperature, current and load on each spring

In order to achieve this on a 16×2 LCD the window platform is used, means each window displays different information and can be switch in between by using “Window” button.

5. Field testing

The completed apparatus was field tested to see how it performs and whether it can provide meaningful data from which conclusions can be drawn.

5.1. Setup

The test bench was loaded with 6 identical springs made from Fort Wayne Metals Nitinol #6 wire ($\varnothing$ 0.381 mm) which

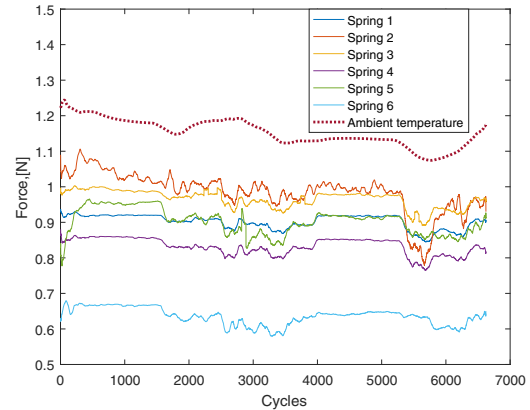


Fig. 6: Force measurements from each load cell and variation in ambient temperature

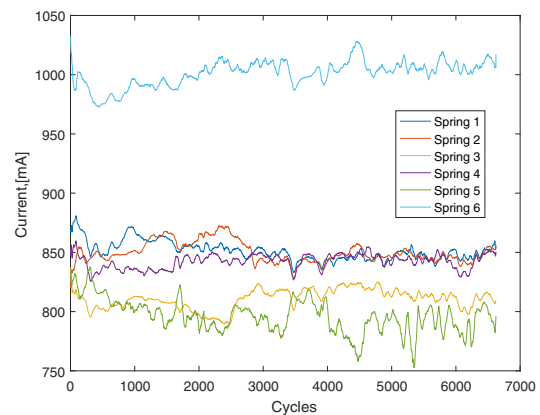


Fig. 7: Current drawn by each spring

are cut from a single length of spring produced with the winder and heated at 400 °C for 10 minutes. Free length of each spring is 7.62 mm (20 active coils), the pitch is 0.381 mm and inner diameter is 3 mm. The springs were then stretched to 55 mm between upper and lower spring holders. Wires were attached to each end with crocodile clips to deliver the electrical current of 5 A total for all springs.

5.2. Data Analysis

The initial calibration run was manually stopped after 42 hours and 14 minutes, during which a total of 6623 actuation cycles were completed. As expected from the literature [2,5] none of the springs failed.

Fig. 6 shows smoothed force measurements from each load cell as well as scaled average of ambient temperature measurements from each heat sensor. Large variation is apparent for all of the springs, which could be attributed to variation in room temperature since there is an obvious positive correlation between the two variables. It also appears that during periods when the temperature is unstable, the measurements fluctuate more without any clear pattern. Load cell 2 stands out in insta-

bility of measurements, which is likely due to the quality of the sensor. Fig. 7 shows current drawn by each spring. Fluctuations in current do not seem to affect the force measured (can be seen from the two stable periods in Fig. 7).

The difference in force measurements between springs is also apparent. Since the spring manufacturing process should ensure good consistency, the explanation could lie in low accuracy of load cells, bad calibration process or even difference in current applied (Spring 6 suggests a negative correlation, but there is insufficient data to draw any conclusions).

6. Results

The limited data from test run does not allow to comment on the degradation of NiTi springs, but it provided valuable insight on the performance of the testing apparatus.

The environment of where the tests take place needs to be maintained at a stable temperature in order to avoid fluctuations in measurements. The reference cell on the test bench did not prove to be of use in compensating for changes in temperature as it read 0.04 N or 0.05 N throughout most of the cycles.

The load cells used seem to vary in quality, some being more consistent than others. Judging from the data, the better ones offer good enough consistency to be able to see degradation with time. It is not possible to comment on the accuracy of measurements without knowing how the actual forces caused by each spring compare, although accuracy is not as important as consistency when researching degradation.

The IR thermometers proved to be inadequate in measuring spring temperature due to their large view angle compared to the size of springs, and did not provide any useful data — readings were only a few degrees above ambient temperature.

The cooling system works as intended — the measurements at the start of each cycle are no more than 15% of the maximum values, therefore defining a cycle.

7. Conclusion

A working test bench was built where all but one functional requirement were met: it is capable of testing 6 springs at once, actuating them with electric current, cooling the springs, measuring tension force and gathering data. Spring temperature measuring, although implemented, does not provide accurate data that could be used.

The top Customer Need CN₀ of providing data on spring degradation and longevity is met provided the tests are run long enough and until the springs fail. Preliminary testing showed that ambient temperature must be better stabilized for better consistency. Some load cells need to be replaced after further testing for reliability.

Despite not being able to measure the springs' temperature, which would have been a nice addition, the Customer Needs are met. The result is a functioning testing bench that is ready for gathering SMA spring data for engineering applications, and therefore the project was a success.

8. Future Work

Heat measurements do not reflect the observed thermal effects. This likely due to the available IR sensors with 90° angle

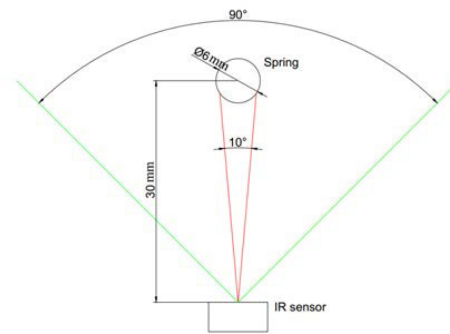


Fig. 8: The difference between 90° and 10° angle of view of IR sensors

of view and that we are measuring a heat of helical spring that is expanded to around 55 mm from its original length of close to 8 mm. That is slightly over 14% of the measurable material of the springs cylinder, where the rest is measures of surroundings. A suggestion of improvement is to exchange the IR sensor [12] from 90° to 10° angle of view and with the same distance, we get better aim on the spring like seen in Fig. 8

An area of concern that is shown in the design matrix Eq. (2) is that of the single power supply for all springs. A future iteration would feature a separate power supply for each spring to ensure equal and stable current through all springs.

References

- [1] Kim S, Hawkes E, Cho K, Jolda M, Foley J, Wood R. Micro artificial muscle fiber using NiTi spring for soft robotics. In: 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems; 2009. p. 2228–2234.
- [2] Waram TC. Actuator Design Using Shape Memory Alloys. ISBN 0-9699428-0-X. Ontario, Canada: Waram Publishing; 1993.
- [3] Suh NP. Complexity. Oxford University Press; 2005.
- [4] Lecce L, Concilio A. Shape memory alloy engineering. Elsevier Ltd.; 2015.
- [5] Einarsson SO. Degradation of NiTi springs through electronic actuation. Reykjavik University; 2016.
- [6] Ireland C. Experimental Statistics for Agriculture and Horticulture. Center for Agriculture and Biosciences International; 2010.
- [7] United Testing System [Webpage]. United Testing System; 2016 [cited 2016 Nov 3]. Available from: <http://www.utscanada.com/application/76/Test-Stand-ESM-303>.
- [8] Suh NP. Axiomatic Design - Advances and Applications. Oxford University Press; 2001.
- [9] Brown CA. Decomposition and prioritization in engineering design. In: Proceedings of 6th International Conference on Axiomatic Design (ICAD). Daejeon, South Korea: Functional Specs Inc.; 2011. p. 41–47.
- [10] Suh NP. The Principles of Design. Oxford University Press; 1990.
- [11] Cochran DS, Foley JT, Bi Z. Use of the Manufacturing System Design Decomposition for Comparative Analysis and Effective Design of Production Systems. International Journal of Production Research. 2016;p. 24.
- [12] Melexis — Inspired Engineering [Webpage]. Melexis; 2016 [cited 2016 Nov 3]. Available from: <https://www.melexis.com/en/documents/documentation/product-flyers/quick-reference-infrared-temperature-sensors>.